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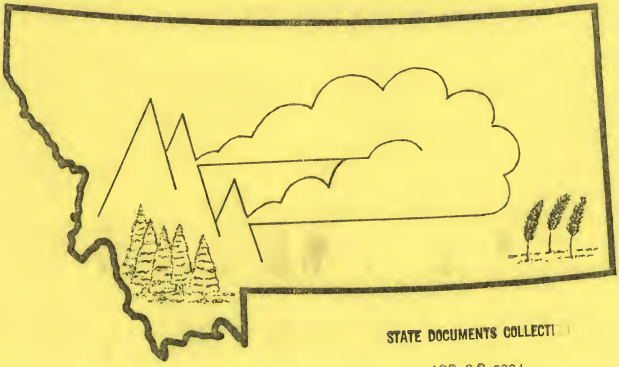
Trip Report - Alzada, MT.
In Situ Solution Uranium Mining
May 22-25, 1979

by

Tom Rediske, Geohydrologist



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MEMORANDUM August 6, 1979

TO: Ed Miller, Chief
Technical Services Bureau

FROM: Tom Rediske, Geohydrologist
Technical Services Bureau

SUBJECT: Field Trip Report for Alzada, Montana Region, May 22-25, 1979, Relative to *In-Situ* Leach Mining and Exploration for Uranium

SUMMARY

During May 22 through 25, 1979, I met with Greg Mills and Alma Plantenberg from the Department of State Lands, for a field investigation of *in-situ* leach mining of uranium in the area surrounding Alzada, Carter County, Montana (Figure 1). Prior to this field trip, I had received several phone calls and personal inquiries from the local inhabitants of this area expressing their concerns for ground water contamination, damage to their water wells, and the protection of their prior water rights, by uranium exploration companies. I began discussion with Greg Mills, Department of State Lands, on the current status of *in-situ* leach mining at Alzada, Montana. There were a few cases in which the activities and plans of uranium exploration companies, as reported to me by the local people of Alzada, were in conflict with activity status reports to State Lands by various uranium exploration companies.

Greg Mills and I decided it would be in the best interest of the State to take a field trip to Alzada in order to confirm conflicting reports about the exploration companies. The trip plan was basically that the Department of State Lands and Department of Natural Resources and Conservation would: 1) investigate where the companies were drilling; 2) see what problems were involved in the uranium exploration; 3) see what area impacts had occurred environmentally; 4) talk with the local inhabitants to see how and if they were being affected; 5) try to identify any possible problems which are associated with *in-situ* leach mining and exploration of uranium; 6) talk with the field personnel of each of the uranium exploration companies and examine their proposed and future plans; 7) obtain names of their exploration staff; 8) discuss the exploration techniques each of the exploration companies are using; 9) consider the general geology in the area; 10) obtain available geohydrologic information from the different uranium exploration companies; 11) identify any drilling problems; 12) identify well hole problems; 13) examine well abandonment along with other techniques and practices; 14) check for water rights violations; and 15) check for reclamation at exploratory well sites.

To summarize briefly my fact-finding trip -

1) There are direct violations in uranium exploration both of the Department of State Lands and of the Department of Natural Resources and Conservation rules and regulations.

2) There is a definite lack of: geohydrologic data, well-monitoring programs, and a basic understanding of the area ground water hydrology.

3) The area has a high potential of cross contamination of the ground

water aquifers due to the improper methods of well hole abandonment by the uranium exploration companies.

4) There are violations in the oil and gas developments, in that wells are not being properly plugged, cased, and grouted in the Alzada area.

In review of findings 1) through 4) above, it is apparent that gross violations of State of Montana rules and regulations are taking place. The probable result of these violations will be a diminishment of the rights of senior appropriators both in quantity and quality of water. I therefore recommend that the Department of Natural Resources and Conservation take an active role in protecting the water rights of the citizens of southeastern Montana.

FIELD TRIP

During May 22 through the 25, 1979, the following information was obtained on my field trip to the Alzada, Montana area. Currently there are three major uranium exploration companies drilling exploration holes in this area, and another company has recently filed for drilling permits.

These companies are as follows:

(1) AMOCO Mineral Comapny, 333 West Hampton, Suite 508, Englewood, Colorado 80110, (303-761-5921);

Project Manager - John Squyres
Senior Geologist - M. J. Maxson
Dr. R.G.Karatsas - Standard Oil of Indiana, Chicago, Illinois

Presently Standard Oil of Indiana is in joint venture with AMOCO Mineral Company. AMOCO's role is to furnish technical assistance and to develop their claims and leases for commercial mining. Standard Oil of Indiana will furnish the capital for this exploration.

Initially, Uranium Resource Incorporated, Richardson, Texas, had an agreement with AMOCO to do their preliminary exploration in Carter County, Montana. On December 1, 1978, the Department of State Lands received a letter from Uranium Resources Incorporated, stating that they had executed an operational agreement with AMOCO and in said agreement, that Uranium Resources Incorporated assigned their exploration rights to AMOCO for their claims and leases in Carter County. This consisted of one hundred drill permits issued by State Lands.

Presently, AMOCO has one hundred drill permits of which ten are drilled and are applying for an additional 300 more. Mr. Mike J. Maxson (AMOCO) and Dr. R. G.Karatsas (Standard Oil of Indiana) met in Helena, Montana on June 14, 1979, at the Department of State Lands with the Department of State Lands, Health and Environmental Sciences, and the Department of Natural Resources and Conservation. AMOCO stated that they were in the process of applying for a permit for a pilot *in-situ* leach plant. They requested each state agency to write to them, in a formal letter, stating what they would have to do for a permit.

(2) Frontier Resource Incorporated, First National Bank Building, 621 17th, Suite 2201, Denver, Colorado 80293, (303-892-1036).

General Manager - J. S. Drever
Controller - Dan St. George
Chief Geologist - Fredrick Smith
On-site Project Geologist - Terry L. Taylor (Alzada, Montana)

Frontier Resource Incorporated is in joint venture with Marathon Oil Company. Frontier Resource Incorporated will furnish technical expertise and Marathon Oil Company will furnish the capital for their exploration and development of their leases and claims.

Presently Frontier Resource Incorporated has 294 permits and have drilled 143. They are applying for 293 additional permits.

On January 4, 1979, Leo Berry, Jr., Commissioner of the Department of State Lands issued an amendment to Notice of Non-Compliance #30, stating:

> On October 30, 1978, the Department of State Lands issued a Notice of Noncompliance #30 to Frontier Resource Incorporated for the drilling of two complete and two incomplete prospecting holes in Carter County, Montana without a prospecting permit pursuant to Chapter 10 of Title 50, R.C.M., 1947, The Montana Strip and Underground Mine Reclamation Act. Since the issuance of that Notice of Noncompliance, the Department has discovered that Frontier Resources obtained and drilled seven holes in violation of the quarter mile relocation allowance. Therefore, the Notice of Noncompliance #30 is hereby amended by adding to the second paragraph, thereof, the following sentences:
>
> > In addition, prior to September 21, 1978, Frontier Resources drilled 49 prospecting holes in Carter County without a valid prospecting permit. Frontier Resources also drilled 7 holes in violation of the quarter mile relocation allowance during 1977 drilling season.

(3) Kerr McGee Resources, Corporation, 401 East E. Street, Casper, Wyoming 82601 (307-237-9318).

Regional Exploration Manager - George Christiansen
Project Geologist - Ken Hatfield
Geologist - Walt Olson, Spearfish, South Dakota (605-642-5748)
Geohydrologsit - Chris Clark, Oklahoma City, Oklahoma (405-270-3971)

Kerr McGee Resource Corporation is a joint venture with Chevron Oil Company, who is furnishing their capital for their exploration company. Presently Kerr McGee has 1102 permits and the estimated drilled wells at approximately 876. They are applying for an additional 464 permits.

(4) Energy Reserve Group, Mineral Exploration Division, 1536 Cole Boulevard, Golden, Colorado 80401.

Landman - Robert Silverman

They've recently applied for 150 well-site permits in the Alzada area.

SOCIAL IMPACTS OF CURRENT AND PROPOSED URANIUM EXPLORATION IN ALZADA AREA

1. AMOCO has one drill rig in use and is anticipating an additional drill rig, log truck, and water truck, to be used in the 1979-1980 season's drilling program. Approximately 24 people will be brought into the Alzada, Montana area. This includes geologists, driller, drivers and mud loggers.

2. Frontier Resources Incorporated currently has two drilling rigs in use and is anticipating one more drill rig, water truck and one more log truck. Approximately 30 people will be brought into the Alzada area. This will include, geologists, drillers, drivers and mud loggers.

3. Kerr McGee has four drilling rigs in use. They have brought in about 36 people which includes geologists, drillers, drivers and mud loggers.

All companies are planning to drill and explore as long as weather permits.

PROBLEMS ASSOCIATED WITH URANIUM EXPLORATION IN THE ALZADA, CARTER COUNTY AREA

The following briefly describes problems which Greg Mills, Alama Plantenberg (Department of State Lands) and I encountered on our joint field trip to the Alzada area.

Photographs (2a,b,c) of NW¼ NW¼ NW¼ of Section 20, Township 9 South, Range 57 East, show an AMOCO drill site, where several uranium exploration wells were drilled in an alkaline seep area. When Greg Mills, Alama Plantenberg and I visited this site, the area was a wet bog compared to the dusty, dry areas surrounding the seep. As you can see in these photos, the site consisted of disturbed ground, two case wells, a mud pit, and several vehicle imprints in the seep area. It is really not known when this area will be dry enough to start reclamation. Potential problems that exist in areas such as this are loss of livestock and denudation of vegetation.

Photographs (2d, e, f, g, h) of the same area as 2a through c, deal with well casing and related problems. When this well was originally drilled, bentonite mud and an organic drilling fluid called "Revert" were used. In April and May of 1979, publications by the Water Well Journal, discussed the controversy which surrounded Revert as a drilling fluid.

Revert has caused bacterial contamination in water wells when used in drilling. Several states have outlawed the use of Revert due to the bacterial contamination of water wells. In talking with Mr. Pete Norbeck (Geohydrologist, Montana Bureau of Mines), he states that when using Revert in drilling water wells or exploratory drilling programs, there is a high potential for bacterial contamination to the well and to the ground water aquifer, especially if there is strong groundwater movement within the aquifer.

Photograph 2d shows the type of drill casing used in these wells. The casing is a spun-fiberglass plastic casing which AMOCO would use in their wells if granted a pilot test permit. During this field trip, Mr. M. J. Maxson (Senior Geologist, AMOCO), and I officially inspected by means of a downhole

camera, two of the wells cased with this type of casing (photos 2f,g, h). According to Mr. M. J. Maxson (photo 2h) his pipe joint is not sealed properly. If this type of problem was to occur and was not caught in a pilot plant or production well, field and if pumped or injected, the well joint could possibly contaminate the groundwater aquifer through a lateral excursion.

Photographs (3a, b, c) of NE¼ NW¼ NW¼ of Section 20, Township 9 South, Range 57 East, show another site drilled by AMOCO. As seen in these photos, this site is in the process of being reclaimed. The top 5 to 10 feet of the well hole is plugged by cement plugs. The problem is that the remainder of the hole is plugged with a quick gel cement. In talking with the Montana Bureau of Mines, this plugging could rupture with time. This well, and other wells plugged by this means, have a high potential for contamination of aquifers. If a pilot plant was set up in the area, as AMOCO intends this well hole could possibly lead to an excursion and could co-mingle with the groundwater aquifer now in use by prior right holders.

Photographs (9a, b) of NE¼ SE¼ NE¼ of Section 25, Township 8 South, Range 57 East, shows a uranium exploration well drilled by Kerr McGee in a reservoir. The abandoned hole is now leaking methane gas probably from the Muddy Formation. It seems to be a low pressure gas, and is probably due to poor well abandonment procedures. In talking with Kerr McGee geologists, they feel it would be difficult, if not impossible, to stop the leaking. In photograph (9b), Greg Mills is shown igniting the bubbling methane gas. (This hole is now plugged).

Photograph (10a, b) of NW¼ SE¼ SE¼ of Section 35, Township 8 South, Range 57 East, at well No. 85728-79, shows the well drilled on the lake shore. It has not been plugged properly. Currently this well would be in violation of State Lands policies (1) drilling within 100 feet of drainage or lake (reservoir) and (2) not being plugged with a seismic cap.

Photograph (11a, b) are in the same vicinity but located 400 feet east. These photos show the damage and "tracks" left while attempting to drill in the reservoir during the early spring and late winter months of 1979. It is not known whether or not they succeeded in drilling the exploration hole in the lake.

Photographs (12a, b) of SW¼ NW¼ NW¼ of Section 27, Township 8 South, Range 57 East, show the cable rig used for a gas exploration hole, prior to 1966. In talking with the Cochran Grazing Association manager, Mr. Waterland, he stated that they have tried to contact the geologist who drilled this well last year in an attempt to get him to remove his drill rig and to fill the mud pit. On inspecting this site, there was methane gas leaking around the well casing. Problems which might occur are co-mingling and cross contamination of ground water aquifers.

Other problems which have been reported to me in conversations with the local ranchers and inhabitants in the Alzada community include water trucks from the different exploration companies withdrawing surface water (without a water permit from the Department of Natural Resources and Conservation) from the Little Missouri River, Thompson Creek, and Willow Creek. When I questioned Terry L. Taylor, on-site geologist for Frontier Resource Incorporated, he stated he didn't think they had to apply for a permit from the Department of Natural Resources and Conservation for their drilling operation.

Problem Summary

1. There is a high probability that there are many uranium exploration wells that are not plugged, or are not plugged properly conforming to legal requirements.

2. There are probably surface water right violations in which exploration drillers have withdrawn water without a water right permit from the Department of Natural Resources and Conservation.

3. There are oil and gas exploration wells not plugged properly.

4. In the area affected by uranium exploration, there are (a) a high potential of cross contamination between ground water aquifers; (b) a static water level drop within the water wells of this area; (c) a possible contamination of ground water aquifers by drilling fluid and; (d) a possibility of damage to the domestic and commercial water right users who have water right permits from the Department of Natural Resources and Conservation for their water wells.

ALZADA COMMUNITY VIEWS

In talking with the local inhabitants of the community, including ranchers and county commissioners, they have concerns, expressed to me, as to what actions the Department of Natural Resources and Conservation proposes to take in order to protect their prior water rights. Many of their water wells are located within the same area as the uranium deposits, and in essence, this formation is the sole supply for their water.

They have stated to me that they are planning to develop irrigation wells within the same formation which is presently being explored by the uranium exploration companies.

The community, as a whole, is not against uranium exploration development, but they want it done properly and with their prior water rights protected.

CURRENT PROBLEMS OCCURRING IN WYOMING IN IN-SITU LEACH MINING

Presently Wyoming's only commercial *in-situ* leach mining operations, Irigaray Uranium Solution Project, is now faced with contamination by excursions of high chloride and alkaline solutions in their monitor test wells. In talking with Mr. Roger Peterson from the Department of Environmental Quality, Land Quality Bureau, he states that there is presently an excursion occurring in the Irigaray site, possibly due to a casing (PCV) failure. It is believed that the casing was overstressed and ruptured, leading to a lateral excursion. He feels that even with the present technology and the current geologic and hydrologic study within the Irigaray project, (done by the U.S. Nuclear Regulatory Commission) that restoration of groundwater quality which was contaminated by the excursion, is not possible. He does feel, however, in the future as technology grows and as *in-situ* leach mining develops, that restoration of an aquifer that has excursion, may be possible.

The present problems in Wyoming are: (1) well hole abandonment (many of the holes drilled in Wyoming are not plugged and even if every hole was plugged properly, at least 10 percent do not seal); (2) well holes that are

not plugged, which have been drilled into an artesian aquifer and are now leaking, causing bogs in which livestock losses are occurring; (3) artesian aquifer, and especially perched aquifer, water levels, have dropped consistently; (4) many sites are not reclaimed; (5) co-mingling of ground water aquifers; (6) exploratory holes that are being drilled and not reported; and, (7) domestic water wells drying up completely.

Mr. Peterson recommends that the state of Montana definitely obtain a baseline study which would give an accurate hydrology, geohydrology, geology, water quality, and air quality study. He also emphasizes that the state monitor the abandonment of exploration well holes. Also, if the state is to issue a pilot plant test permit, that the state should limit the size to a five spot well field and realize that in all actuality, that under current technology, the area may not be restored. Every pilot plant and well field should be intensely studied and the state should monitor these wells.
The strongest comment stated by Wyoming Department of Environmental Quality, was: Any state which is faced with uranium *in-situ* leach mining and exploration, must have a state agency or a group of state agencies with a conscience for the protection of their citizens. These agencies must regulate, control and protect prior rights of their citizens before permanent damage does occur. Due to the lack of control, regulation and monitoring in the beginning stages of *in-situ* mining and exploration in Wyoming, Wyoming is presently faced with serious problems and they do not know if they can be corrected.

Montana is now faced with these same problems and in review of the lack of coordination, manpower and reluctance for involvement in *in-situ* leach mining, I would have to say the same problems will occur and are occurring now in Montana.

GEOLOGIC SETTING

Alzada, Montana is located in the very southeastern corner of Montana and is part of the Great Plains physiographic province (Figure 1). The area of influence, from solution mining surrounding Alzada, is approximately 756 square miles (1958.04 square m) and is located structurally and topographically on the northern nose of the Black Hills arch. The surface configuration in the Alzada area is characterized by gentle rolling uplands, which have been extensively dissented, and by broad valleys. The dominant drainage of the area is the Little Missouri River and its tributaries which have downcut, entrenched, and formed a dendritic drainage pattern.

CLIMATE AND WATERSHED

This area is considered a typical semi-arid climate with extensive diurnal changes in temperature. The average yearly precipitation is approximately 13 inches indicating relatively low humidity in the area.

During conference discussions with DNRC hydrologist, Larry Brown, the following hydrologic information was developed.

> Surface water production in this type of watershed is dependent upon and limited to, spring runoff and isolated precipitation events.

Various U.S. Geological Survey (USGS) records, including those from crest gages and perennial streamflow recorders, indicate wide variation in discharges from the sub-basin. Spring runoff and flash floods produce flows in excess of 150 ft^3/second from the smaller watersheds. Most streams are intermittent, running only in relationship to precipitation events, snowmelts, and springs dependent on local aquifers for recharge. Generally, spring runoff occurs from March through May, and lasts from 3 to 18 days in most watersheds depending primarily on area, aspects, soil types, temperatures, and vegetation. Flows of less than 1 ft^3/second are prevalent during most runoff seasons.

The Little Missouri River's average annual discharge is approximately 81.8 ft^3/second or 59,220 acre-feet per year. Extreme discharges during spring runoff may exceed 6000 ft^3/second. Average seasonal peaks are about 500 to 950 ft^3/second. Summer flows of approximately 20-35 ft^3/second are common. Flows of less than 1.0 ft^3/second are common during the winter months when ice formation occurs throughout the watershed.

REGIONAL GEOMORPHOLOGY

Figure 3 represents a photographic overview of the regional geomorphology in the Alzada, Montana area where uranium exploration is presently taking place. Photographs 1A through 8A characterize aspects of the regional geomorphology of the area affected by uranium exploration. Each geological formation discussed is based on Stratigraphy and Structure of the Northern and Western Flanks of the Black Hills Uplift of Wyoming, Montana and South Dakota, as described in USGS Professional Paper, 404, 1964.

Photographs 1A through 6A are from a series of pictures which were photographed in the middle of Township 9 South, Range 57 East, on a NW to SE trending ridge. This ridge represents a major topographic high (≈ 3850') and is located structurally on the western flanks of the northern plunge of the Black Hills arch (Figure 4).

Photograph 1A, SE¼ SE¼ NW¼ of Section 21, Township 9 South, Range 57 East, facing east; over looks the northern plunge of the Black Hills arch. The topography in this area can be considered part of a breached anticline structure in which the crest of the northern plunge of the axis of the anticline has been deeply eroded by the Little Missouri River and its tributaries. The breaching of the anticline by the Little Missouri and its tributaries seems to be structurally controlled and is reflected by the drainage patterns that are orientated in the NW-NE trend perpendicular to the NW to SE axis of the Black Hills arch (Figure 4).

With time, this area has developed into a small topographic basin in which the flanks of the arch are represented by moderate ridges forming topographic highs on the structural flanks of the anticline.

Photograph 2A facing north, NW¼ NW¼ NW¼, Section 20 Township 9 South, Range 57 East, shows several uranium exploration wells, in tight-pattern formation, which were drilled in an alkaline seep area. Note the white sodium dispersion in the area and the lack of any vegetation. The geological formation exposed is the middle member of the Upper Cretaceous, Turner sandy member of the Carlile Shale formation. The Turner is characterized by gray sandy shales and silt stones

with numerous beds of light yellow or reddish-brown, weathering, silty and ferruginous limestone, concretions, 150 to 260 feet thick.

Photograph 3A, facing southeast in the NE¼ NW¼ NW¼ of Section 20, Township 9 South, Range 57 East, is another uranium exploration site drilled in January of 1978. This site is supposedly in the process of reclamation by the uranium exploration company. The disturbed areas with no vegetation and the white marker with an orange top is the drillpad and exploratory well hole. The geological formation exposed here is still the Turner sandy member.

Photograph 4A is located in the same location as Photograph 3A, but is facing northwest. The disturbed ground in the bottom of the photograph is the drillpad. Note the black stained area located in the center of the picture along side and on the road. This residue consists of a mud slurry mixture of drilling mud and drill-cuttings. In the top right hand side of the photograph a bare steep bank is seen. This is the exposed contact between the bottom unit of the Upper Cretaceous Carlile formation, top Sage Breaks member and the underlying Turner sandy member. The Sage Breaks member is a gray noncalcareous shale with numerous beds of light gray, weathering, septarian limestone concretion, 200 to 300 feet thick.

Photograph 5A facing northeast in the SE¼ NW¼ NW¼ of Section 21, Township 9 South, Range 57 East is looking down a dendritic tributary of Willow Creek. The rolling topograpny and sparse vegetation is fairly characteristic of this area. The geologic formation exposed here is the Upper Cretaceous, concretionary facies of the Green Horn formation. The concretionary facies is a noncalcarous gray shale with zones of light gray, weathering, septarian concretions in the central part of the area thinning to 70 feet westwardly.

Photograph 6A facing north, SW¼ SW¼ SW¼ of Section 32, Township 8 South, Range 58 East, shows an excellent example of vegetation and sodium dispersion occuring in this area. The soil profile consists of a high sodium, bentonitic composition. The geologic formation here is the Upper Cretaceous, Belle Fourche Shale formation in which the betonite rich deposits will be developed for commercial openpit mining. The Belle Fourche Shale is a dark shale with numerous purplish red, weathering, siderite concretions in the lower part, and light gray and yellowish gray, weathering limestone concretions in the middle and upper parts, 350 to 850 feet thick in the upper part of the gray red bentonite beds.

Photographs 7A of NE¼ NW¼ SE¼ of Section 35, Township 8 South Range 57 East, and 8A of NW¼ NW¼ SE¼ of Section 14, Township 8 South, Range 57 East show the lower stream terraces and valley basin. The geologic formation in this area is recent alluvial deposits in bands 5 miles in length and 50 feet thick. The area consists of well drained, moderately fine textured to fine textured soils. Typically the surface layer is light brownish, silty clay loam. The sub-soil is a heavier, light yellowish, brown silty clay loam. This type of area is primarily in rangeland with some being developed for dryland farming, irrigated hay and small grains.

STRATIGRAPHY AND STRUCTURE

The stratigraphic bedrock units that outcrop in the area affected by uranium exploration are sedimentary. As discussed on pages 12-14, the surface geology is dominated by upper Cretaceous outcrops (Figure 4). Along the outside border of this area, younger, upper Cretaceous, Paleocene, and younger sedimentary units are exposed. As previously mentioned this area lies structurally on the northern plunge of the Black Hills arch.

Structurally the Black Hills arch is a broad northwest trending anticline uplift approximately 200 miles long and 70 miles wide. The flanks of the structure border the Williston Basin to the northeast, and the Powder River Basin to the west and southwest. Figure 5 is an outline map of the area relating the Black Hills uplift and nearby structural features. Within the Black Hills uplift, the strata has been upwarped to form a dome whereby older rocks have been exposed toward the center and the younger rocks along the flanks of the structure. These outcrop patterns are structurally controlled by the Black Hills arch.

The regional lithology of each individual stratigraphic unit varies from area to area. USGS Professional Paper 404 (Stratigraphy and Structure of the Northern and Western flanks of the Black Hills uplift, Wyoming, Montana, South Dakota, 1964), best describes the general lithology. The sedimentary rocks exposed on the northern and western flanks of the Black Hills arch in the mapped area have an aggregated thickness of about 11,000 feet and range in the age from Mississippian to Quaternary. There rocks may be divided into 23 formations, exclusive of surficial deposits of Tertiary and Quaternary ages. The distribution of the formations is shown by the geologic map (Figure 4). A summary of their thickness and lithology is given in table 1.

All the sedimentary rocks, from the Pahasapa limestone of Mississippian age to the Wasatch formation of Eocene age, are about concordant in dip, although deposition was not continuous as shown by unconformities at the base of the Minnelusa formation of Pennsylvanian and Permain age, the Opeche formation of Permian age, the Gypsum Spring formation of Middle Jurassic age, the Sundance formation of late Jurassic age, and the Fall River formation of early Cretaceous age. The Wasatch formation and older rocks were deformed and eroded during early Tertiary time. The White River formation of Oligocene age was deposited unconfomably on the uplifted older beds.

Rocks of marine and nonmarine origin occur equally. The Mississippian Pahasapa limestone is marine. Pennsylvania, Permian, and Triassic rocks probably were deposited mostly in shallow marine embayments. Marine sediments were deposited over the area during parts of Middle and Late Jurassic time, followed by nonmarine deposits in Late Jurassic and part of Early Cretaceous time. Much of the Cretaceous is represented by a thick marine sequence beginning with the Skull Creek shale and ending with the Fox Hills sandstone. Younger Cretaceous and Tertiary rocks are nonmarine.

As much as 600 feet of sedimentary rocks, older than Mississippian, outcrop parts of the Black Hills uplift east and southeast of the mapped area. The thicknesses and lithologies of these rocks are summarized in table 1. They include strata of Late Cambrian, Early and Middle Ordovician, and Early Mississippian age. In addition, sedimentary rocks of Silurian, Devonian, and Late Mississippian age were found during drilling operations in the Williston basin north of the Black Hills. Equivalent strata may extend varying distances southward via the subsurface into southern Carter and Powder River Counties,

Montana, and perhaps into northern Crook County, Wyoming.

SUBSURFACE GEOLOGY

The stratigraphic units that are being explored by the uranium exploration companies and all the major economic uranium discoveries within the Black Hills arch are contained within strata of the lower Cretaceous Iyan Kara group. The Iyan Kara consists of subequal amounts of complex interbedded and intertongued sandstone and claystone. The group is bound below by continental Jurassic sediment of the Morrison formation and is overlain by marine, lower Cretaceous Skull Creek shale.

Presently the principle economic uranium deposits are occurring from one to five miles downdip at a depth ranging from 100 to 600 feet. Within the Alzada, Montana, area the occurrence of uranium deposits are at a depth ranging from 1000 to 2500 feet.

The Iyan Kara group, as seen in table 1, is divided formally into lower Cretaceous system, Lakota and Fall River formation. These are generally considered nonmarine deposits or respectively continental and marginally marine. (Bergndahl, et.al. 1961; Robinson, C.S., et.al., 1964; Renfro, A.R., 1969).

The Lakota formation ranges regionally within the structure from 45 to 300 feet thick. The thickness varies within a short distance. The basal Lakota strata are discontinuous, green, red, brownish red, greenish gray, claystone and siltstone facies that grade into a sandstone facies of a light gray, fine to coarse grain, cherty, quartzite sandstone which contains abundantly disseminated carbon in a porefilling pyrite matrix. In many places the complex interfingering sequence of claystone to sandstone to claystone facies are present.

A. R. Renfro (1969), breaks the Lakota formation into two different stratigraphic units: basal unit as just described and the uppermost units which is a lenticular, greenish gray to light gray to dark purplish gray claystone to sandstone to siltstone sequence. This sequence is characterized by carbonatious fragments and ferruginous material throughout the formation. Channel features and distems are common throughout the Lakota (Robinson, et.al., 1964; Renfro, A.F., 1969).

The different uranium geologists in Alzada, tend to divide the Lakota formation into three mappable units with the middle member being an intermittent discontinuous bed throughout the formation. This is an important consideration to take into account when looking at the local geohydrology of this area.

In section 20, Township 9 South, Range 57 East, several exploration wells were drilled into the Lakota formation in a localized area of approximately 200 square feet. Within this pattern of wells the static water level varied considerably. Each well was drilled to a different depth within the Lakota formation, thus encountering a good representation of the different hydrologic properties of each of the stratigraphic units within the Lakota.

I believe that on a regional scale, the Lakota can be considered as single hydrological unit. In the Alzada area each ten acre drilling unit should be viewed as a separate hydrologic unit. The Lakota formation is a reliable water source for the community of Alzada for stock, irrigation, and domestic water consumption.

The Fall River formation overlies the unconformable surface of the Lakota formation, with thickness ranging from 95 to 200 feet. It consists of a fine to medium grain light yellow brownish sandstone with innerbedded gray black shales and gray siltstones. The claystone, siltstone and shales are relatively thin beds. Again this is a regional variation. On the whole, the formation contains an abundance of ferrinuginous materials in the form of "matrix pyrite" and carbonaceous material widespread throughout the formation. The Fall River thickens regionally from southeast to northwest at the expense of the underlying Lakota formation. (Robinson, et.al., 1964; Renfro, 1969).

Figure 6 is a regional profile of the Iyan Kara group in a normal depositional sequence with a coarse grain sequence of the Lakota formation and a fine grain of the Fall River sandstone. This represents the approximate and distribution sequence of a single time transgressive depositional system of the lower Cretaceous sequence.

HYDROLOGY

The different hydrologic aquifers which may be affected by uranium exploration, and from possible developments of *in-situ* leach uranium mining, are surface alluvium, New Castle formation, Fall River formation, Lakota formation, and the Sundance formation. Presently, little information is known about their hydrological characteristics. It appears that recharge to these aquifers in the Alzada area is located in the center of the Black Hills arch where these formations outcrop. Recharge to these formations is by precipitation stream flow loss (where stream flow components are either vertically, laterally, or longitudinal, to the direction of ground water flow), and/or an upward migration from the deep seated aquifers (C. G. Bowlers, 1963; Hagameyer, 1971).

Figure 4 besides representing the structural map of the northern plunge of the Black Hills arch in the Alzada area, probably represents the regional ground water flow. As seen in Darcy's equation, ground water flows from the level of high potential to that of the low potential, and in most cases potential gradient is controlled by topography with gravity as the driving force. One would assume, within this area, that the ground water flow follows the direction of the dip of the structures which regionally dip northward.

The hydrologic and geohydrologic data compiled in this area is negligible. There is very little ground water control in the eastern part of Montana. The most up-to-date studies in the area are being done by the USGS but this is limited to the Mississippian system, Madison formation (Pahasapa formation) which is located several thousand feet below the lower Cretaceous stratigraphic series. Other studies done in the area were by Eugene S. Perry; Miller, M.R., et. al., 1977, State of Montana Bureau of Mines and Geology.

Talking to Mr. M. R. Miller, a co-author of the above publication from the Montana Bureau of Mines, he states that the information that was published for Alzada, Montana, is not a complete representation. Many of the wells in the area are not recorded within the Bureau of Mines nor with the Department of Natural Resources and Conservation. But even with the deficiency of this study, it does show that there are some water wells within the same stratigraphic formation that is being explored by the uranium exploration companies. During

conversations with many of the local people, and from my personal experience in this region, we found that a few people in the community have had their own water well drilling rigs. That during the early middle and late-middle 1900's many water wells were drilled and not recorded, and are still being used today.

Due to the lack of geohydrologic data, calculations with any degree of accuracy cannot be made to estimate the amount of ground water flow, transmissivity and storage coefficients, or the degree of hydrologic connections between these aquifers. There aquifers are presently being used as a beneficial water supply for commercial, live stock, irrigation, and by uranium exploration companies in the area.

SOLUTION MINING (IN SITU LEACHING OF URANIUM)

This section provides background information on solution mining (*in situ* leaching) of uranium. All of the following information, except rollfront deposit and figure 11, 12, and 14 was obtained from the final environmental statement related to the Wyoming Mineral Corporation, Irigaray Uranium Solution Mining Project, (Johnson County, Wyoming), Document #40-85-02. This was prepared for the U.S. Nuclear Regulatory Commission, Washington D. C. on September, 1978.

IN SITU LEACH MINING

In situ leaching (solution mining) of uranium is a potential addition to the list of conventional mining methods currently used to extract uranium. Basically, the *in situ* leaching method involves: (1) the injection of a leach solution (lixiviant) into a uranium-bearing ore body to complex the contained uranium; (2) mobilization of the uranium complex formed; and (3) surface recovery of the solution bearing the uranium complex via production wells. Uranium is then separated from the leach solution by conventional milling unit operations (ion exchange).

The environmental advantages of *in situ* leaching of uranium appear to be significant. While the conventional extraction of minerals produces significant impact on the environment, the solution mining method appears potentially to result in a lesser impact. Compared with the conventional uranium mining and milling operations, *in situ* leaching will also permit economical recovery of currently unrecoverable low-grade uranium deposits, thereby enhancing the nation's uranium reserves.

In conventional uranium recovery techniques, the ore is mined (open pit or underground), crushed, ground in mills, and subsequently leached, using either an acidic or basic oxidizing solution to extract the uranium. In solution mining, an acidic or basic oxidizing solution is injected into the produced from the naturally situated ore body via wells to extract the uranium. The chemical technology is about the same in both cases. In solution mining, however, no ore mining, transporting, and grinding operations are needed before chemical processing to recover the uranium. Moreover, there are no mill tailings to be disposed of, although solid wastes are generated that would require controlled disposal.

In conventional uranium mining, for each ton of mined ore, more than 1900 pounds of solid waste (tailings) are produced, containing essentially all of the associated radium-226 and other daughter products. With solution mining, less than 5% of the radium from an ore body would be brought to the surface.

Since the technology for *in situ* solution mining of uranium is still actively developing, variations among the different operations are not unusual. Thus, the following background discussion is general.

For consistency and clarification, two major terms are defined.

Solution mining

Solution mining is a general term describing the extraction of minerals in liquid form. The solution may only contain the mineral sought from the natural source (e.g., salt, sulfur) or may include other materials such as excess chemicals that have been added to aid in the dissolution of the resource from its source host, reaction by-products, and other materials associated with the mineral deposit co-dissolved in the process.

The mineral-bearing solution can be obtained from its source in several ways. A fluid can be injected and recovered through wells from the mineralized host beneath the surface (borehole mining) or sprayed over mineral-bearing materials that have brought to the surface (e.g., dump or heap leaching). In all cases, a solution containing the mineral sought is produced.

In situ leaching

In situ leaching is one of the many types of solution mining. In this technique, the mineral sought is dissolved from its host source *in place* (*in situ*) and extracted as a liquid, while leaving the solid host material in its natural position. The basic unit operations of *in situ* leaching of uranium involve: (1) the introduction of a leach solution via injection wells into a uranium-bearing ore body; (2) mobilization of the uranium from the host material via creation of a soluble complex salt; and (3) removal of the complexed uranium-bearing solution via production wells. The uranium in the uranium-bearing solution is recovered in a conventional surface facility where, generally, an ion exchange process is used for recovery.

Process Description

Uranium *in situ* solution mining involves the following basic components and associated processing activities: (1) the ore body; (2) the well field; (3) the lixiviant or leach liquor; (4) the uranium recovery process; (5) the waste treatment process(es); (6) waste management process(es); and (7) aquifer restoration and land reclamation process(es). The interrelationships of these are discussed in the following.

Ore Body

Rollfront uranium deposits are generally associated with fluvial sandstone and conglomerates. The origin for the primary source of the uranium deposits seems to be a matter of great debate. What is clearly understood is that uranium is highly water soluble in an oxidation environment and has a stron affinity to carbon in a reducing environment.

The criteria for a favorable environment for an uranium rollfront deposit protore is that sediment has to be deposited in a sandstone with abundant carbonaceous material throughout the formation. The carbonaceous material is in the form of plant life and animal life as deposited and entrapped during the

time of deposition of the formation. The Fall River and the Lakota formation in the Alzada area meets this criteria.

Events following burial of this sediment includes initial stages of carbonization and fermentation of plant and animal material (carbonaceous), co-products, anaerobic bacteria and thiobacillus which produce hydrogen-sulfide and hydrogen. This in turn precipitates available iron in the form of pyrite. Uranium in solution is being carried by ground water. The uranium in motion was leached from some definitive source such as an grantic arkosic rock or a tuffaceous rock, (possible the White River and/or Fort Union formations).

The ground water which carried the uranium was that of a slightly alkaline water in the HCO_3+SO_4 and SO_4+HCO_3 carbonate complex. This ground water dissolved and transported the uranium into the flow system or ground water aquifer. As the water entered the aquifer it was probably rich in oxygen, but with the increase in flow length there is a decrease in oxygen resulting in a reducing environment. Thus, when the uranium entered a reducing area with a limited amount of carbonaceous material, the uranium and associated minerals were deposited creating a lean protore deposit (Hagemaier, 1971, and Rackley R. E., etc., 1968).

With time, as the water flowed through the protore stratigraphic unit a complex physical biochemical reaction takes place altering the stratigraphic unit. As described in the R. L. Rackely paper (1968).

> "The zone of reaction is a solution front or roll. The changes which took place in the rock inside the solution front is alteration. The solution front, and the alteration it produces, is called a geochemical cell. These cells, which began at this early stage, grew like smouldering fires and ultimately coalesced and spread as reactive constituents were fed to and enveloped by the cells."

Figures 7-9 illustrate the typical uranium rollfront deposit, mineral distribution, rock type, and principal reactions found in this type of deposit. Elements that are generally associated with the ore deposit are uranium, arsenic, selenium, vanadium, molgbdenum, manganese, iron, calcite, and a small amount of boron. Other elements show an increase in concentration in the ground water such as cadmium, copper, nickel, zinc, silver, and lead. But these minerals are less than a few parts per million and show no relationship to the uranium mineralization.

The rollfront geometry is generally controlled by the variations of the permeability within the sandstone unit. Most of the cell shapes are irregular. Figure 7 shows an idealized geochemical rollfront cell in which the lead edge of the rollfront is pointed down the hydrostatic gradient of the aquifer. The cell may be elongated and parallel to the channel but in idealized section, the cells are convexed outward. Within the Alzada area, some uranium geologists feel that the longitudinal dimension may range from 500 feet to 100 feet, and thickness as much as 25 feet to 100 feet. Figure 8 is the best model of rollfront deposits. Note the irregular shape of the ore zone in relationship to the protorezone within the stratigraphic unit.

As time progesses the geochemical cells migrate farther down the hydrologic gradient, continouly reprecipitating the uranium out of the protore deposit, which then concentrates the uranium in the form of U_3O_8 within the rollfront.

Hagemaier (1971), describes the ground water chemistry in relationship to the rollfront as that where all the uranium anomalie are found the ground water chemistry was HCO_3+SO_4 and SO_4+HCO_3. The uranium was precipitated somewhere in the transition zone between the SO_4+HCO_3 and the HCO_3 ground water facies. The reason for the chemical change in the ground water is due to the reduction of sulfate from the solution by anaerobic bacteria. Thus looking at a horizontal cross section of the rollfront deposit, the protore ground water chemistry is SO_4+HCO_3 and the altered zone behind the rollfront is HCO_3+SO_4 (Figure 7). Uranium rollfront in the Alzada area is in all probability still in a dynamic state and is still moving down the hydrologic gradient of the aquifer, with geologic time increasing in size and concentration (ppm) of uranium.

Well Field

The well field provides the means by which leach solution (lixiviant) is circulated through the ore body to extract the uranium. Therefore the well field design determines the effectiveness of lixiviant circulation, confinement, and utilization. It also affects the efficiency of uranium extraction. Principal engineering considerations in well field design are the well spacing, the injection and production patterns, the well completion methods, and the number of wells to be used. Well spacing is determined by the hydrologic characteristics of the formation. These influence the rate and efficiency of lixiviant circulation. The pattern of injection and production wells is determined by the injectivity rate(s) to the formation and the horizontal hydraulic sweep efficiency through the mineralized well field zone. The well completion method and local permeability determine the vertical confinement and vertical sweep efficiency of the lixiviant through the mineralized zone. Figure 10 and 11 show typical well field lay out, note the manifolding of the pumped wells.

Lixiviant chemistry

Initially, *in situ* solution mining of uranium utilized a dilute sulfuric acid lixiviant enhanced by an oxidizing agent such as sodium chlorate. Such a lixiviant is suitable in working low-alkaline (low-carbonate) ore deposits. However, acidic solutions also tend to dissolve other trace minerals associated with such an ore and, therefore are less specific for uranium. As a result, basic (ammonium or sodium bicarbonate-carbonate) lixiviants with an oxidizing agent are now generally used in most *in situ* activities where carbonate minerals are known to be associated with the ores (Table 2).

Table 2. Estimated chemical feed rates for WMC Irigaray uranium recovery process

500,000 lb/year production

[illegible]	Feed rate	
	Pounds per hour	Tons per year
Lixiviant chemicals for 800 gpm injection		
[illegible]	75–225	325–985
[illegible]	40–120	175–525
Hydrogen peroxide (H_2O_2, 150%)	75–250	325–1100
Elution and precipitation reagents for 4.5 gpm total eluant bleed		
[illegible]	35–100	150–440
[illegible]	75–200	325–875
Hydrochloric acid (35% HCl)	25–75	110–325
Ammonia (NH_3)	5–20	22–90
Fuel		
[illegible]	20–50	90–220

At startup, the necessary chemicals are added to water drawn from the ore zone aquifer. This solution is then recirculated through the localized ore zone (well field). Typically, the desired concentration of a basic lixiviant (e.g., ammonium bicarbonate) is maintained by chemical reconstitution operations and by controlling the pH (about 8). Carbon dioxide and ammonia or other soluble basic carbonate salt may be used to adjust concentrations. An oxidant (oxygen, air, or hydrogen peroxide) is normally added to the lixiviant at the well field prior to its injection into the ore zone.

Uranium Recovery Process

As depicted in Figure 12, a generalized solution mining process has four main processing circuits or units: (1) a lixiviant sorption circuit, (2) a resin transfer circuit, (3) an elution and precipitation circuit, and (4) a product drying and packaging unit. The movement of uranium through these circuits and the relationships of various process components are discussed in the following section.

Lixiviant Sorption Circuit

The lixiviant sorption circuit consists of the ore body, the well field, the uranium adsorption column(s), lixiviant bleed, lixiviant makeup unit, and calcium control unit. The process begins with the injection of lixiviant into the ore body. This solution oxidizes the uranium in the localized ore zone and forms a soluble uranium ion complex. The complexed uranium, mobilized reaction by-products, and unreacted reagents in the lixiviant flow to a production well and are pumped to the surface (produced from the ore zone). This uranium-bearing solution then passes through a uranium sorption column (near the well field or in the recovery plant) via the use of an ion exchange resin that preferentially extracts the uranium ion complex from the pregnant solution. The solution leaving this resin column is essentially barren of uranium. It also contains residual lixiviant chemicals. This barren solution is passed to the makeup unit, where it is reconstituted with the necessary lixiviant chemicals and is recycled to the well field for reinjection.

A solution bleed in the plant enables some control of ground water flow. By diverting part of the barren solution leaving the uranium sorption column, less recycle solution is reinjected. This reduces the water level in the localized ore zone, permitting water from the surrounding aquifer to migrate into the mined zone. The rate of the groundwater incursion should be equal to the bleed rate. This groundwater influx would tend to limit the excursion of lixiviant out of the localized well field area.

The presence of calcium compounds in the lixiviant or barren solution is generally disadvantageous in the processing. Calcium could precipitate as calcite ($CaCO_3$) in basic leach solution or as gypsum ($CaSO_4$) in sulfuric acid leach solution. Either precipitate could plug injection and production wells or interfere with the ion exchange process. Calcium removal units utilizing either ion exchange (water softening) or solution pH control techniques may be placed in the lixiviant sorption circuit to mitigate potential calcium-related problems.

Resin Transfer Circuit

The ion exchange resin used in the uranium extraction column is eluted periodically to recover the sorbed uranium and to regenerate the resin before it is returned to the sorption circuit. The resin transfer circuit cycles the ion exchange resin between the sorption and elution circuits. Most

solution mining operations house the ion exchange columns in a recovery building. Alternatively, the ion exchange columns may be located near the active well fields and the resin trucked to a central recovery facility (satellite recovery system).

The resin transfer circuit also allows the flushing of the uranium-loaded resin and rinsing of the regenerated (eluted) resin to control other contaminants that may affect the efficiencies of the elution and the extraction process respectively.

Elution and Precipitation Circuit

The elution and precipitation circuit consists of the elution column, the precipitator, and the contaminant control and eluant makeup units. Uranium-loaded resin from the column is the feed for this circuit. After transfer of the loaded resin to the elution column, the uranium-loaded resin is eluted with a moderately concentrated chloride salt solution (1 to 2 *M* Cl). The chloride ion in this solution displaces the uranium ion complex sorbed on the resin and thus regenerates the resin. The regenerated resin is returned to the uranium extraction column, and the uranium-rich eluate is transferred to the precipitation unit.

In the precipitation unit, the desorbed uranium ion complex is destroyed by acidification. The resultant uranium ion is precipitated with ammonia as ammonium diuranate $\{(NH_4)_2U_2O_7\}$, which is commonly known as ADU. The ammonium diuranate, in slurry form, is transferred to the drying and packaging unit. The barren eluate is recycled through the contaminant control unit and eluant makeup unit to the elution column.

In the uranium recovery process, contaminants such as sulfate and vanadium are also sorbed on the ion exchange resin and stripped into the elution and precipitation circuit along with uranium. In the absence of any control, the concentration of such contaminants could build up to affect the product purity and/or elution process efficiency. For contaminant control, a bleed-off of some of the contaminated recycle eluant is effected by replacing a bleed volume with an equal amount of fresh eluant. This controls the contamination level but requires the increased use of makeup water and elution chemicals and the discharge of a concentrated liquid waste stream to a holding pond that must be ultimately managed.

Water consumption can be reduced through the use of precipitation and physical absorption processes in contaminant control. For example, sulfate levels can be controlled by the addition of barium chloride ($BaCl_2$) to the recycle eluant, precipitating insoluble barium sulfate ($BaSO_4$). This can be stored in an interim solid waste impoundment; vanadium can be adsorbed on activated carbon and recovered as a by-product or disposed of with the carbon as a solid waste.

The nature, level, and even the need of contaminant control depend on the composition of the ore body and the chemistry of the specific solution mining process. The prevailing conditions in the solution mine field, the chemical reagent costs, and the wastewater disposal techniques employed will determine what contaminant control measures will be used.

Prior to entering the elution column, the recycle eluant passes through an eluant makeup unit. In this unit, the chloride ion concentration, depleted during elution and contaminant control operations, is restored by the addition of a chloride salt. Makeup water may also be added here to maintain the system flow.

Product Drying and Packaging Unit

The uranium leaves the elution and precipitation unit as a slurry of ammonium diuranate and may be dried prior to packaging for shipment. Upon entering the product drying and packaging unit, the slurry is washed and dewatered. The rinse water, which contains some soluble uranium, is returned to the elution and precipitation unit. The moist diuranate cake enters a dryer and calciner, where it is converted to U_3O_8 and the by-products (water and ammonia) are driven off. Following drying and calcining, the oxide product (yellow cake) is crushed and placed in drums for shipment.

To mitigate particulate uranium releases in this unit process, the exhausts from the dryer and calciner, crusher, and packaging equipment areas are treated in Venturi scrubbers. The spent scrubber solution is recycled to the elution and precipitation circuit to recover any entrained uranium.

Waste Effluent Treatment Processes

In general, liquid and solid waste and atmospheric effluents will result from the solution mining activities. Liquid wastes from well field overpumping (i.e., production flow in excess of injection flow), elution and precipitation circuit bleeds, and subsequent aquifer restoration represent the major waste streams to be managed from solution mining activities. Since the dissolved solids content of the wastewater precludes any uncontrolled releases, some form(s) of waste management is necessary. Generally, for liquid waste management, evaporation ponds are utilized; however, deep well disposal has been used in Texas. The ponds vary in size depending on the flow rate of liquid waste streams to the pond and the rate(s) of water evaporation and seepage from the pond. To minimize unwanted seepage of the wastewater, the ponds are lined during construction with clay, asphalt, or continuous plastic membranes. The specific method(s) used is dependent on the conditions at each solution mining operation.

Solar evaporation is a consumptive use of water. When recycle of wastewater is desirable, water reclamation by reverse osmosis, ion exchange, chemical treatment, or multi-effect distillation may be attempted.

Solid wastes generated, for example, from the calcium control unit in the lixiviant sorption circuit and from the contaminant control unit in the elution and precipitation circuit also require controlled management. During the life of a solution mining operation, solids may be impounded in specific storage ponds as a slurry and be maintined and monitored under a liquid seal to minimize particulate emissions and radon gas evolution. Permanent disposal techniques, in accord with NRC and/or responsible state agency regulations, will subsequently isolate the solids from the environment.

Sources of atmospheric emissions include the open surfaces of ponds and tanks, the product drying and packaging unit, the internal combustion engines in vehicles and drilling rigs used at the site, dust due to vehicular movement on

unimproved roads, and processes using ammonia. Tank emissions can be limited by venting them through liquid or solid absorbents before release to the atmosphere. Venturi or impingement scrubbers are used to control both particulate and gaseous emissions from drying and packaging operations. Exhaust emission controls are presently provided for internal combustion engines.

Groundwater Quality Restoration Process

After termination of solution mining operations, procedures are implemented to restore the water quality of the affected aquifer. Restoration will remove or immobilize chemical species injected into or mobilized as a result of chemical actions in the ore body during mining. The restoration process is intended to reduce the mobilized species content and composition of the groundwater to levels set to levels set by appropriate regulatory agencies.

Groundwater restoration technology is still in the development stage. A process that requires the pumping of large quantities of water from the aquifer (groundwater sweeping) is currently in general use. By this technique, the contaminated water removed from the aquifer is replaced by groundwater entering the localized ore zone from the surrounding area or is replaced by purifying (for example, by reverse osmosis) the contaminated water and recycling it into the aquifer. The water entering this ore zone aquifer will gradually sweep the residual impurities from the solution mining operations toward the production wells, where they will be withdrawn to the surface for management. The efficiency of the sweeping action may not be very high. Impurities, e.g., ammonia, are chemically sorbed on clay minerals within the aquifer host formation and are only removed slowly, because their migration rate is retarded by repeated sorption and desorption from the clays. Unless some efficient elution or immobilization techniques are developed, long-term aquifer pumping may be the only method of ore zone groundwater restoration. Water produced by such a restoration process or other processes under development should be managed.

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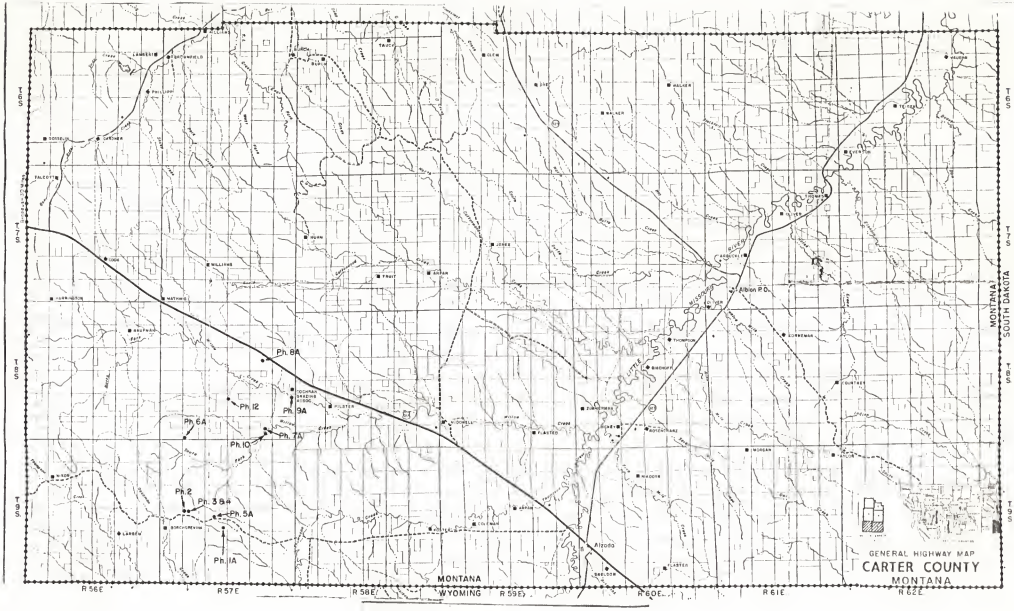
Generalized section of the exposed sedimentary rocks on the northern and western flanks of the Black Hills uplift

System	Series	Stratigraphic unit				Thickness (feet)	Description
Quaternary	Recent and Pleistocene	Alluvium and stream terraces					Silt, sand, and gravel.
		—Unconformity—					
Tertiary	Oligocene	White River formation				0- 180	Light-gray medium- to coarse-grained sandstone at base overlain by light brownish-gray claystone and siltstone.
		—Unconformity—					
	Eocene	Wasatch formation				300+	Grayish-yellow sandstones and gray shale, numerous coal beds; thick extensively burned coal bed (Roland) bed of U.S. Geol. Survey Bull. 798-A) at base.
	Paleocene	Fort Union formation	Tongue River member			500- 800±	Yellowish-gray massive sandstone and light-gray shale; numerous coal beds; thickest in Montana; thins southward.
			Lebo shale member			250- 290	Medium- to dark-gray shale, light-gray sandstone, and a few thin coal beds.
			Tullock member			500-1,100	Light-gray and light-brown sandstone, gray shale, and numerous thin coal beds; thinnest in Montana; thickens southward.
Cretaceous	Upper Cretaceous	Lance formation				300-1,600	Gray to yellowish-gray sandstone and gray shale; a few thin beds of carbonaceous shale; thinnest in Montana; thickens southward.
		Montana group	Fox Hills sandstone	Colgate member, 50-100 ft.		125- 200	Brown sandy shale and siltstone, light-gray sandstone, and brown ferruginous sandstone concretions; the Colgate member, a prominent massive white sandstone, at top in Montana.
			Pierre shale	Upper part	Kara bentonitic member, 140-240 ft.	800-1,800	Dark-gray shale and claystone; locally beds of siltstone; abundant limestone concretions some fossiliferous in upper and lower parts; thickens southward from Montana. Kara and Monument Hill bentonitic members, gray bentonitic shale and impure bentonite with a few limestone concretions and small barite concretions.
					Monument Hill bentonitic member, 130-220 ft.		
				Mitten black shale member.		145-1,000	Dark-gray to black shale with beds of yellowish-gray bentonite at base and numerous large yellowish-brown-weathering fossiliferous septarian limestone concretions in upper part; thickens southward from Montana.
				Cheyenne River member	Groat sandstone bed, 0-125 ft.	0-1,000	Light-gray claystone and shale with abundant reddish-brown iron-stained concretions and thin lenses of bentonite. Groat sandstone bed, mapped north of T. 52 N., consists of gray fine-grained glauconitic and ferruginous sandstones.
		Colorado group	Niobrara formation			150- 225	Chalk marl and calcareous shale; numerous thin beds of bentonite, dark gray when fresh, weathers light yellow.
			Carlile shale	Sage Breaks member		200- 300	Grayish-black noncalcareous shale with numerous beds of septarian limestone concretions that weather light gray.
				Turnip sandy member		150- 260	Dark-gray shale, locally sandy and silty, with numerous beds of light-yellow and red silty limestone concretions; commonly a thin bed of light-gray medium-grained sandstone at the base.
				Lower unnamed member		40- 150	Dark-gray shale with a few limestone concretions; locally slightly silty and sandy; thickest in Montana.
			Greenhorn formation			70- 270	In northeastern and southeastern parts gray calcareous shale and marl with some brown-weathering, thin-bedded limestone; in central part, gray noncalcareous shale containing prominent light-gray weathering septarian limestone concretions; thins westward.
			Belle Fourche shale			250- 450	Dark-gray to black shale with numerous dark purplish-red weathering siderite concretions in lower part, and several beds of light-gray and yellow-weathering limestone concretions in middle and upper parts; thickens westward.
	Lower Cretaceous	Colorado group	Mowry shale			150- 230	Dark-gray siliceous shale, weathers light gray; numerous fish scales along partings; many thin bentonite beds; Clay Spur bentonite bed on top.
			Newcastle sandstone			0- 95	Lenticular beds of light-gray sandstone and siltstone and dark-gray shale and claystone; a few beds of impure coal and bentonite; thickness varies within short distances, and averages about 40 feet.
		Skull Creek shale				150- 270	Black shale with a few dark-red ferruginous concretions.
		Inyan Kara group	Fall River formation			95- 200	Fine- to medium-grained light yellowish-brown to brown sandstone with interbedded gray and black shale and gray siltstone; averages about 125 feet in thickness near its outcrop.
			—Unconformity—				
			Lakota formation			45- 300	Light yellowish-gray to white fine- to coarse-grained sandstone and conglomeratic sandstone irregularly interbedded with red, green, yellow, gray, and black claystone; coal beds near base locally; thickness varies within short distances.
Jurassic	Upper Jurassic	Morrison formation				0- 140	Greenish-gray, green, and grayish-red claystone with a few thin discontinuous beds of light-gray sandstone and limestone; thickness at most places between 90 and 120 feet.
		Sundance formation	Redwater shale member			30- 195	Greenish-gray soft fissile sandy and silty shale; includes some thin beds of glauconitic sandstone and oolitic and coquinoid limestone; thickness at most places between 140 and 190 feet.
			Lak member			40- 80	Yellow and pink crudely bedded fine-grained sandstone and siltstone.
			Hulett sandstone member			35- 50	Yellowish-gray fine-grained thin-bedded to massive calcareous sandstone; locally pink northeast of Devils Tower.
			Stockade Beaver shale member			50- 90	Soft gray calcareous shale with some thin beds of yellowish-gray sandstone.
			Canyon springs sandstone member			0- 40	Friable yellowish-gray or pink sandstone, some light greenish-gray siltstone.
		—Unconformity—					
	Middle Jurassic	Gypsum Spring formation				0- 135	At base, massive white gypsum with interbedded red crystalline limestone; overlain near Hulett by interbedded gray cherty limestone and red claystone; thins southward from a maximum observed thickness of 135 feet near the junction of Deer Creek and the Belle Fourche River (SW¼ sec. 13, T. 33 N., R. 64 W.).
		—Unconformity—					
Triassic and Permian		Spearfish formation				450- 625	Red sandy shale, siltstone, and sandstone; beds of massive white gypsum in lower half.
Permian		Minnekahta limestone				40±	Light-gray thin-bedded limestone, pink on outcrop.
		Opeche formation				80- 90	Reddish-brown and maroon fine-grained sandstone, siltstone, and shale.
	—Unconformity—						
Permian and Pennsylvanian		Minnelusa formation				400- 800	Light-gray and tan sandstone, gray limestone and dolomite, red shale, local gypsum and anhydrite.
		—Unconformity—					
Carboniferous	Mississippian	Pahasapa limestone				500- 600	Light-gray limestone, locally dolomitic.

TABLE 1

From, Stratigraphy & Structure of The Northern and Western Flanks of the Black Hills Uplift, Wyoming, Montana,& South Dakota, USGS Professional Paper 404


GENERAL HIGHWAY MAP
CARTER COUNTY
MONTANA
MONTANA
WYOMING
MONTANA
SOUTH DAKOTA
R 56E
R 57E
R 58E
R 59E
R 60E
R 61E
R 62E
T 9 S
T 8 S
T 7 S
T 6 S
T 5 S
Ph. 8A
Ph. 12
Ph. 9A
Ph. 6A
Ph. 7A
Ph. 10
Ph. 2
Ph. 3 & 4
Ph. 5A
Ph. 1A
Albion P.O.
ALZADA
ALZADA
BOX ELDER
BOX ELDER
CUSTER
CUSTER
EKALAKA
EKALAKA
FALLON
FALLON
LOCKWOOD
LOCKWOOD
MILES CITY
MILES CITY
MOSSTOWN
MOSSTOWN
PORTER
PORTER
SOUTH FORK
SOUTH FORK
WIBAUX
WIBAUX
WOLF CREEK
WOLF CREEK
YELLOWSTONE
YELLOWSTONE
BIG OTTER CREEK
BIG OTTER CREEK
BIG SANDY CREEK
BIG SANDY CREEK
BIG SANDY

MEAN ANNUAL PRECIPITATION, IN INCHES
(Data from U.S. Weather Bureau–ESSA)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

FIGURE 2

Precipitation map of Montana

1 A

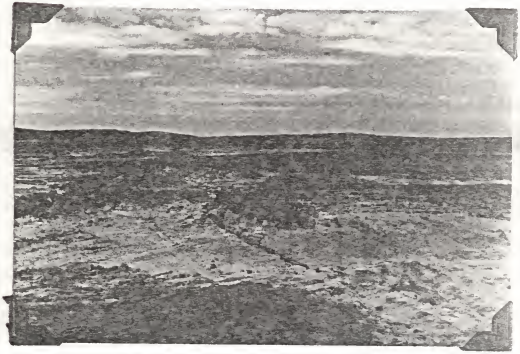
SE¼,SE¼,SE¼, Sec. 21, T.9S, R.57E,
Overlooking the northern plunge of
the Black Hills arch

2 A

NW¼,NW¼,NW¼, Sec.20, T.9S, R.57E.
Amoco's well site in a alkaline seep
area. Carlile Shale, Turner Sandy Member
(KCT)

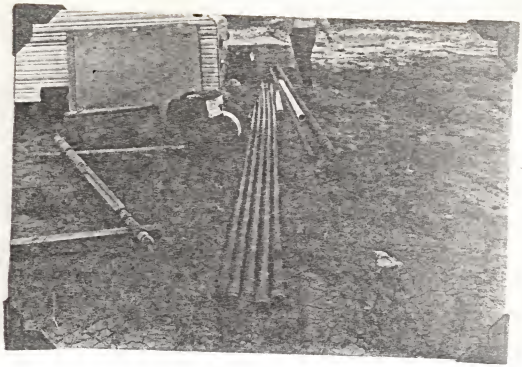
2 B

Drill mud pit, to wet in this area
to reclamate



2 C

Tracks - disturbed ground from the drilling
in the seep area



2 D

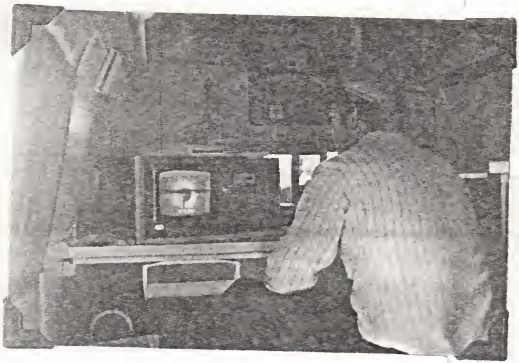
Fiberglass plastic well casing used in
Amoco test holes

2 E

Well inspection of well casing by down
hole camera

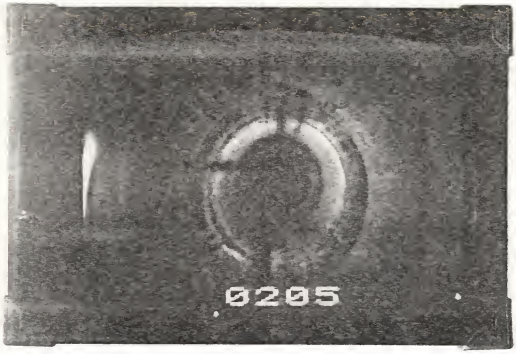
2 F

Down hole camera, well head and tripod
for well inspection



2 G

Down hole T.V. camera monitor,
control units - in rear of minivan



2 H

Well casing joint viewed on T.V. monitor
at 205 (bad joint)

3 A

NE¼ NW¼ NW¼, Section 20 Township 9 South
Range 57 East, Amoco drill site
Carlile shale, Unnamed Formation (KCL)

3 B

Plugged hole - plugged with quick jell

4 A

Contact of Carlile formation (Top Sage Break member) with underlying Turner Sandy member. Note black stain of mud slurry and drill cuttings.

5 A

SE¼ NW¼ NW¼, Section 21, Township 9 South
Range 57 East Green Horn formation

6 A

SW¼ SW¼ SW¼, Section 32, Township 8 South
Range 58 East Bell Fourche Shale
formation

7 A

NE¼ NW¼ SE¼, Section 35, Township 8 South, Range 57 East Alluvial fill, silts, sands and gravels

8 A

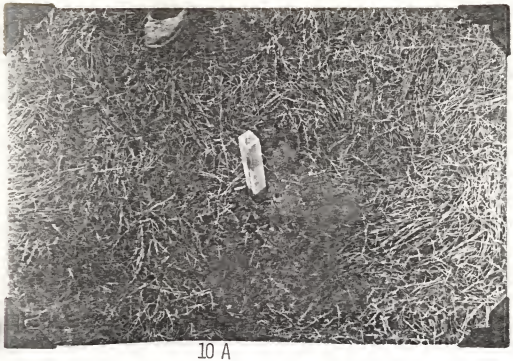
NW¼ NW¼ SE¼ Section 14, Township 8 South, Range 57 East Alluvial fill, silts, sands and gravels

9 A

NE¼ SE¼ NE¼, Section 25, Township 8 South, Range 57 East Methane gas escaping from a plugged exploration hole drilled into the edge of a reservoir

9 B

Greg Mills (D.S.L.) igniting escaping gas bubbles



10 A

NW¼ SE¼ SE¼, Section 35, Township 8 South, Range 57 East improper plugged uranium hole. Note - no cememt plug

10 B

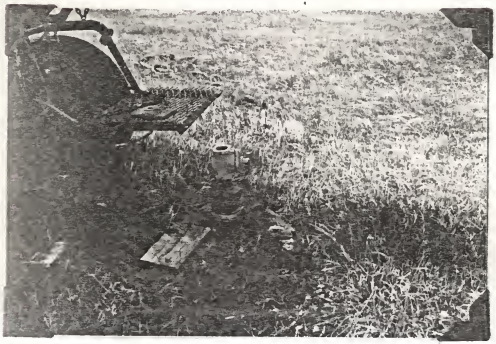
Same location as above

11 A & B

In same vicinity of 10A Note - damage and tracks left while attempting to drill in the reservior during early spring by an uranium exploration drill rig.

12 A

SW¼ NW¼ NW¼, Section 27, Township 8 South, Range 57 East Abandoned oil and gas cable rig - drilled prior 1966



12 B

Well Head Leaking Methane Gas

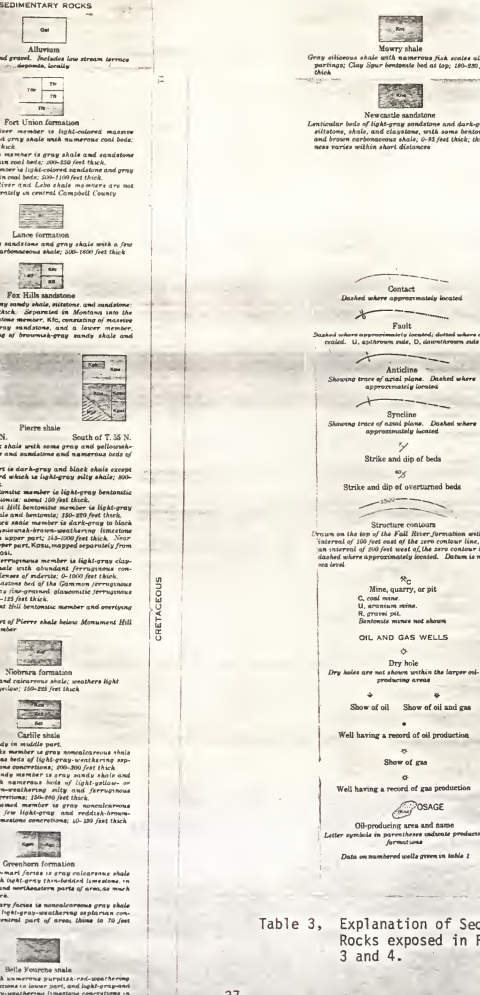


Table 3, Explanation of Sedimentary Rocks exposed in Figures 3 and 4.

CAMP CREEK
Cottonwood
Creek
Butte
Creek
Gravel
Pleistocene
Creek
Qal
Kal
Kcs
Kb
Qu
Ka
Ks
Kw
Kr
Kf
Kc
Ki
Kn
Kmr
Ke
Kp
Kpl
Kt
Ku
Kv
Km
Kk
Kwr
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Kn
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Kv
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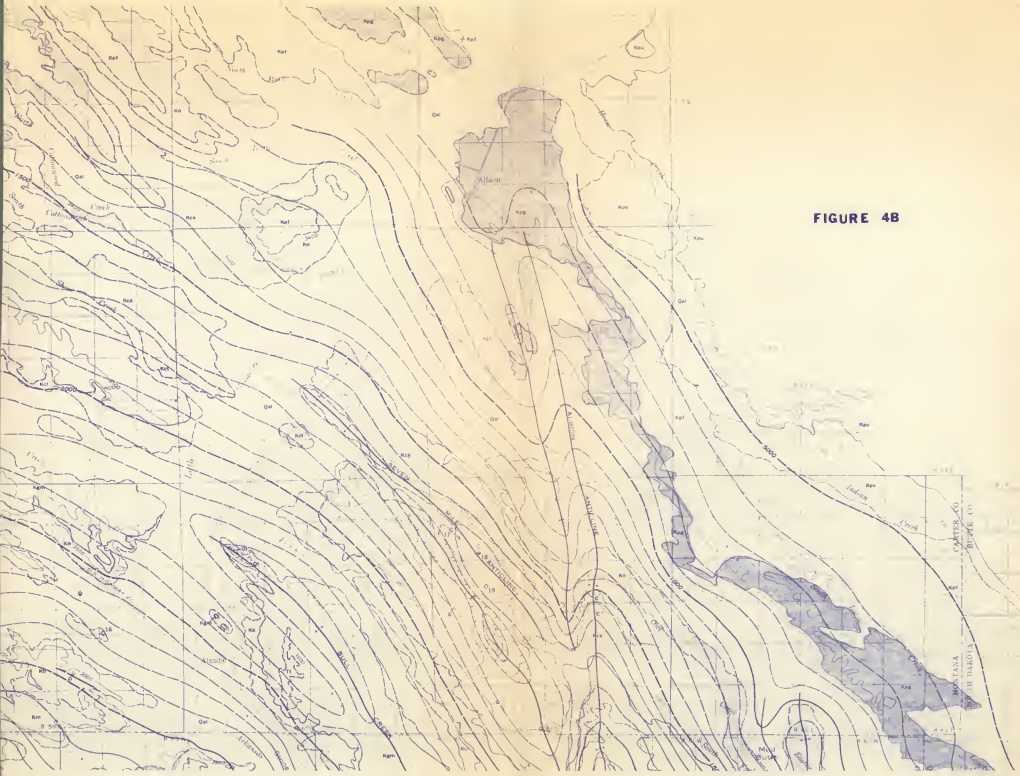
Kwr
Kr
Kf
Kc


Albion
Indian Creek
CARTER CO.
BIG HORN CO.
MONTANA
SOUTH DAKOTA
Kaf
Kas
Kau
Qal
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Kgu
Kgl
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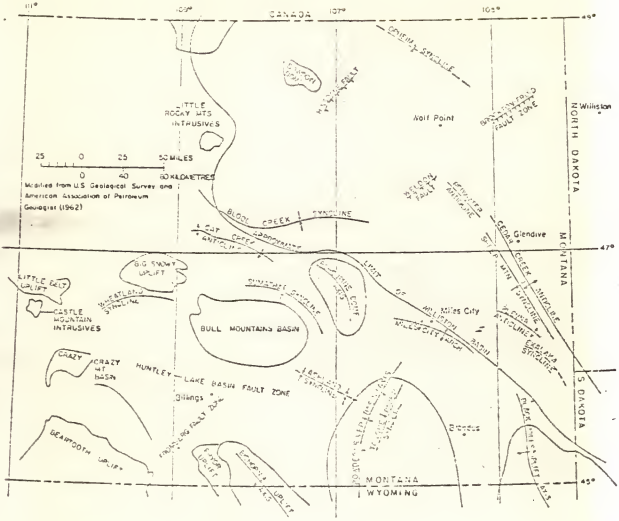
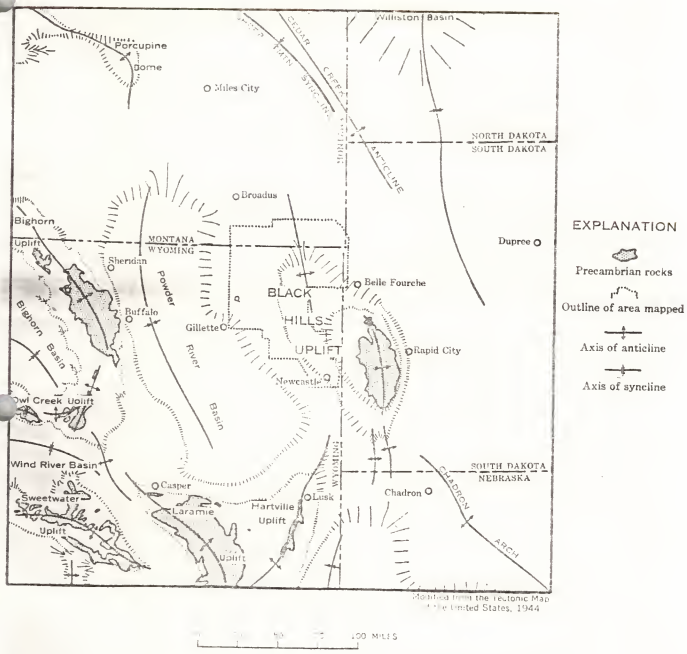
Qal
Qal



From Hopkins, Water Resources Data for Deep Aquifers of Eastern Montana

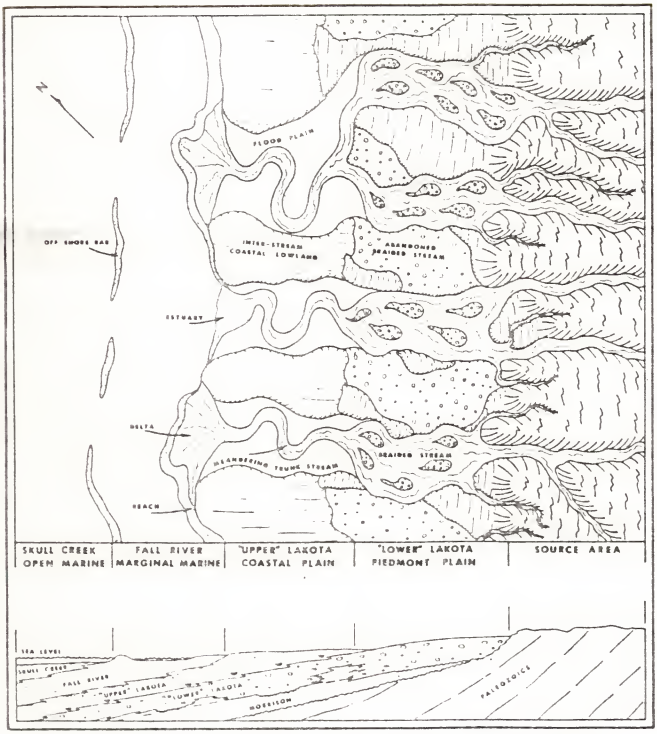
FIGURE 5 A



Generalized map showing the Black Hills uplift in relation to nearby structural features.

From, Stratigraphy and Structure of the Northern and Western Flanks of the Black Hills Uplift, Wyoming, Montana, South Dakota. USGS Professional Paper 404

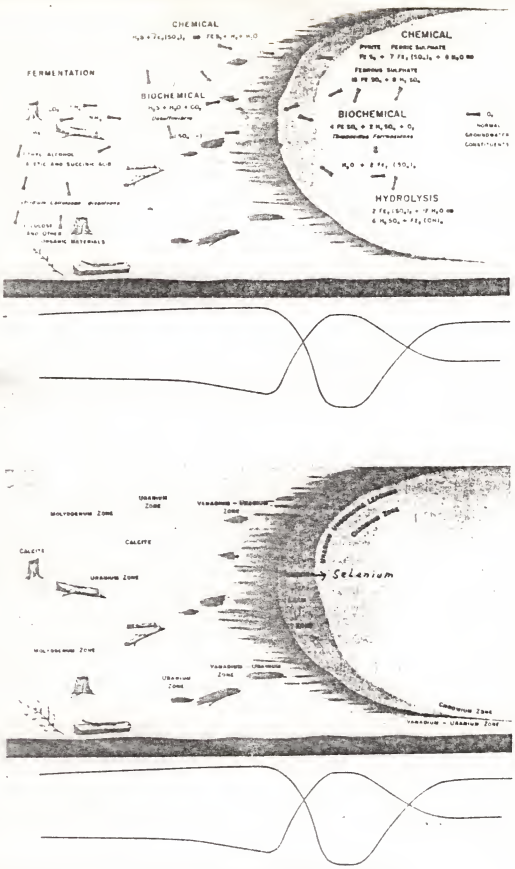
FIGURE 5 B



Diagrammatic Paleo environment map and Cross Section of the Inyan Kara Group.

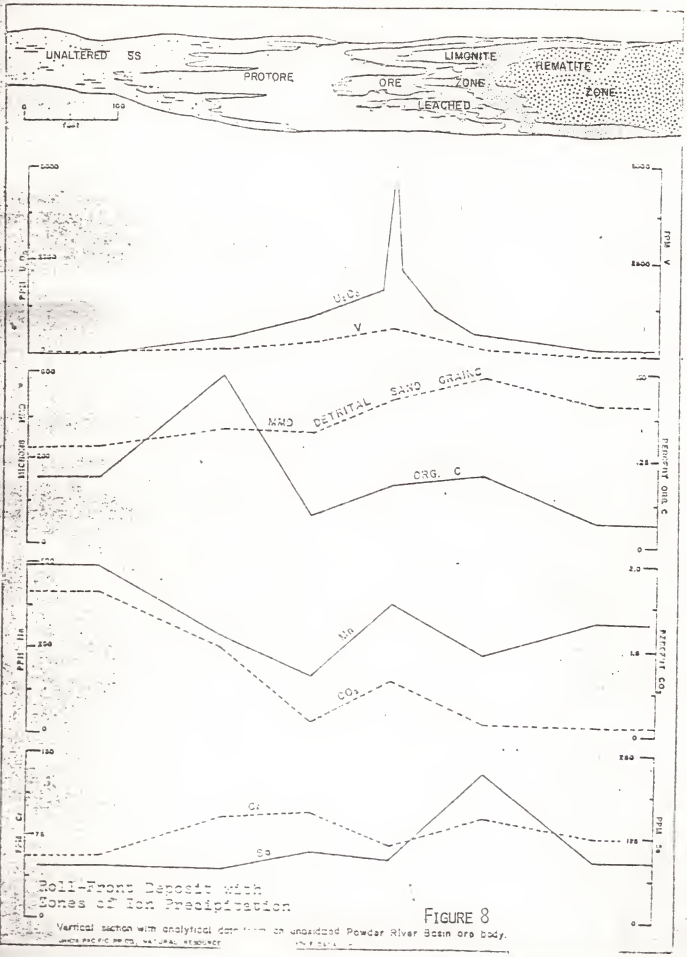
From, Uranium Deposits in the Lower Cretaceous of the Black Hills, A.F.Renfro
Contribution to Geology, Wyoming Uranium Issue, V01.8, 2, pt 1 Summer 1969

FIGURE 6



FROM, R.I. RACKLEY, P.N. SHOCKEY AND M.D. DAHILL, 1968

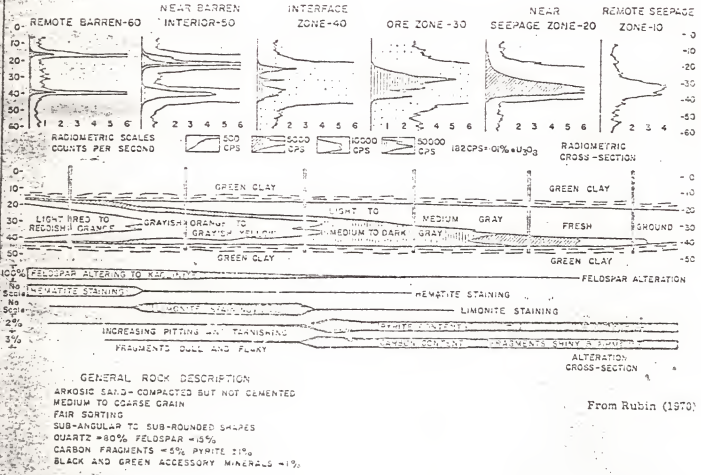
FIGURE 7



Roll-Front Deposit with Zones of Ion Precipitation

FIGURE 8

Vertical section with analytical data from an unoxidized Powder River Basin ore body.



GENERAL ROCK DESCRIPTION

ARKOSIC SAND-COMPACTED BUT NOT CEMENTED
MEDIUM TO COARSE GRAIN
FAIR SORTING
SUB-ANGULAR TO SUB-ROUNDED SHAPES
QUARTZ ≈80% FELDSPAR ≈15%
CARBON FRAGMENTS ≈5% PYRITE ≈1%
BLACK AND GREEN ACCESSORY MINERALS ≈1%

From Rubin (1970)

From Bobaru 1975 and Rubin 1970

ROLL-FRONT URANIUM DEPOSIT WITH ZONES OF ROCK ALTERATION

FIGURE 9

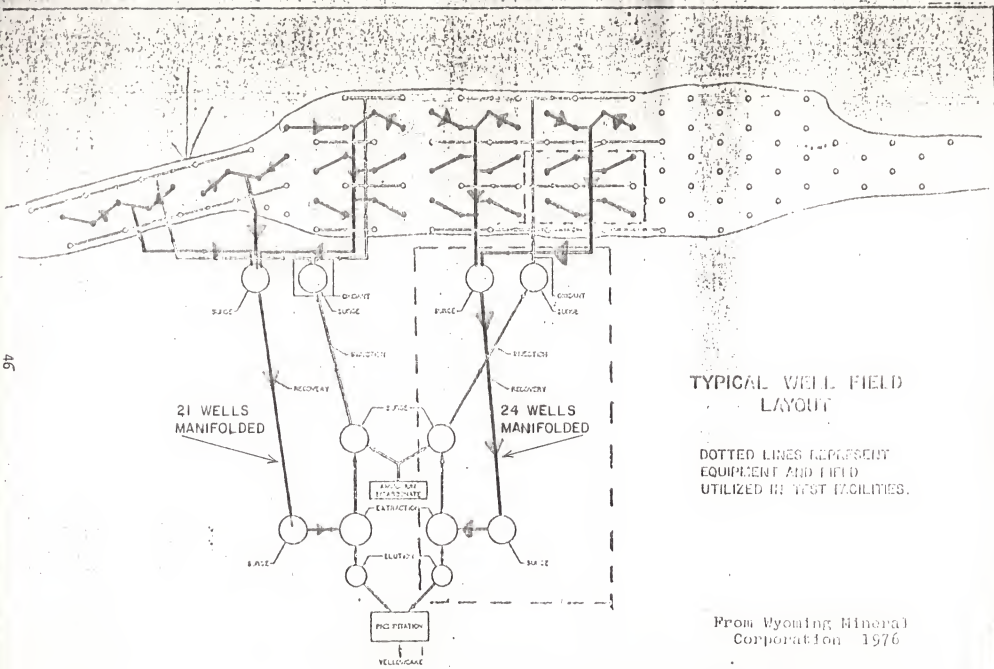
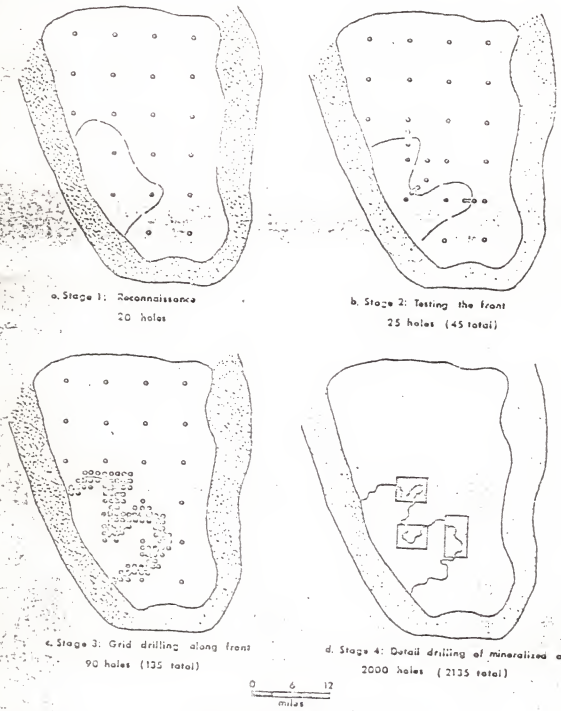

21 WELLS
MANIFOLDED
24 WELLS
MANIFOLDED
SURGE
RECOVERY
ELUTION
EXTRACTION
PRECIPITATION
YELLOWCAKE
TYPICAL WELL FIELD
LAYOUT
DOTTED LINES REPRESENT
EQUIPMENT AND FIELD
UTILIZED IN TEST FACILITIES.
From Wyoming Mineral
Corporation 1976

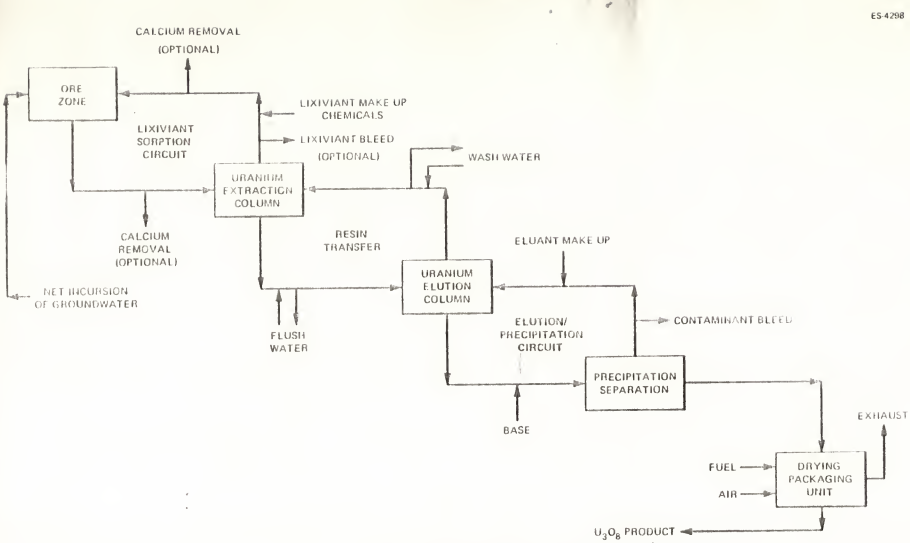
FIGURE 10



From Boberg 1975

HYPOTHETICAL DRILLING SEQUENCE FOR URANIUM

FIGURE 11.

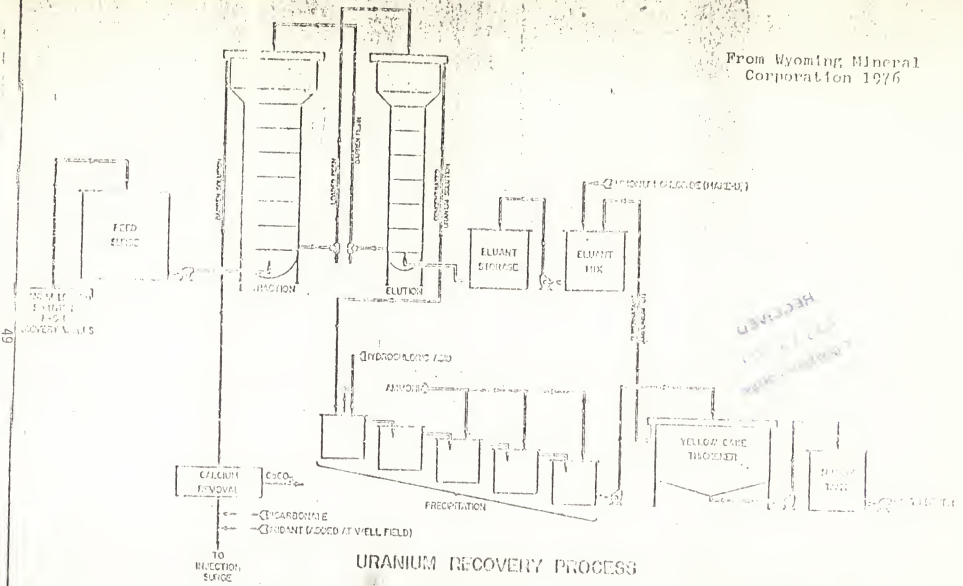


Generalized uranium recovery process.

FIGURE 12

From,Final Enviromental Statement related to the Wyoming Mineral Corp. Irigaray Urnaium Solution Mining Project. Docket 40 8502

From Wyoming Mineral Corporation 1976



URANIUM RECOVERY PROCESS

FIGURE 13